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(NASA-TM-X-71716) EXPERIMENTAL TRANSIENT
TURBINE BLADE TEMPERATURES IN A RESEARCH
ENGINE FOR GAS STREAM TEMPERATURES CYCLING
BETWEEN 1067 AND 1567 K (NASA) 30 p HC
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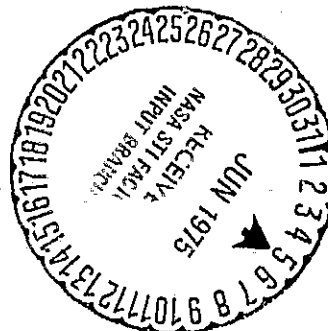
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**EXPERIMENTAL TRANSIENT TURBINE BLADE TEMPERATURES IN A RESEARCH
ENGINE FOR GAS STREAM TEMPERATURES CYCLING BETWEEN 1067 AND 1567 K**

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April, 1975



ABSTRACT

Experimental transient turbine blade temperatures were obtained from tests conducted on air-cooled blades in a research turbojet engine, cycling between cruise and idle conditions. Transient data were recorded by a high speed data acquisition system. Temperatures at the same phase of each transient cycle were repeatable between cycles to within 3.9 K (7° F). Turbine inlet pressures were repeatable between cycles to within 0.32 N/cm² (0.47 psia). The tests were conducted at a gas stream temperature of 1567 K (2360° F) at cruise, and 1067 K (1460° F) at idle conditions. The corresponding gas stream pressures were about 26.2 and 22.4 N/cm² (38 and 32.5 psia) respectively. The nominal coolant inlet temperature was about 811 K (1000° F).

**EXPERIMENTAL TRANSIENT TURBINE BLADE TEMPERATURES IN
A RESEARCH ENGINE FOR GAS STREAM TEMPERATURES
CYCLING BETWEEN 1067 AND 1567 K
(1460° AND 2360° F)**

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SUMMARY

E-8328

Experimental transient turbine blade temperatures were obtained from tests conducted on air-cooled blades in a research turbojet engine, cycling between cruise and idle conditions. Transient data were recorded by a high speed data acquisition system. Temperatures at the same phase of each transient cycle were repeatable between cycles to within 3.9 K (7° F). Turbine inlet pressures were repeatable between cycles to within 0.32 N/cm² (0.47 psia). The tests were conducted at a gas stream temperature of 1567 K (2360° F) at cruise, and 1067 K (1460° F) at idle conditions. The corresponding gas stream pressures were about 26.2 and 22.4 N/cm² (38 and 32.5 psia) respectively. The nominal coolant inlet temperature was about 811 K (1000° F).

INTRODUCTION

Experimental transient temperature data for an air-cooled turbine blade were obtained in a research turbojet engine.

High performance engines of the future are expected to operate at increased turbine inlet temperatures. The materials being used in today's engines for the fabrication of turbine blades and vanes are presently being pushed to the limit of their structural capabilities. Thus, much attention is being given to the problems of cooling turbine blades and vanes under conditions of

transient and steady-state operation. The knowledge of their transient temperature response is important in evaluating thermal fatigue lives of blades and vanes. In previous studies at the NASA-Lewis Research Center (refs. 1 to 4), the steady-state heat transfer and life characteristics of some blade and vane cooling configurations were investigated. References 1 and 2 describe experimental steady state temperature distributions for air cooled vanes tested in a static cascade and a modified turbojet engine, respectively. References 3 and 4 described analytical studies involving stress analysis of air cooled turbine blades. Experimental transient turbine vane temperatures obtained in a cascade are reported in reference 5. The transient temperatures were reported to be reproducible to within 11 K (20° F). However, little information is available on the transient heat transfer characteristics of air cooled turbine rotor blades.

The purpose of this report is to measure the transient thermal response of an air-cooled turbine blade and to determine the reproducibility and control of the data acquisition system. Another purpose of the report is to describe a fuel control system that can be used for obtaining reproducible engine transients.

Experimental data were obtained for a five-blade sector installed in the rotor of a research turbojet engine. The gas stream temperature was cycled between typical cruise and idle conditions of 1567 and 1067 K (1460° and 2360° F), respectively. The engine wheel speed cycled between 6800 and 8200 rpm. The gas stream total pressure at cruise condition was 26.2 Newtons per square centimeter (38 psia). The cooling air temperature was nominally 811 K (1000° F). The coolant flow was set to limit the hot-spot blade temperature to 1200 K (1700° F).

APPARATUS

The blades that were investigated for their transient temperature response were installed in a turbojet engine that was modified to permit testing of air-cooled turbine blades. A complete description of the engine and the support facilities of the test cell is given in reference 6. For the transient temperature response tests, a control system was also installed to

operate the engine during the cyclic operation. A brief description of the engine and the cyclic control system is given below.

Engine and Facility Description

The research engine incorporated a modified high pressure spool and combustor assembly from a two-spool J-75 turbojet engine. A major feature of this engine is the provision for two separate and distinct cooling air systems in the rotor assembly. The turbine rotor consists of 76 blades. A five-blade sector in the rotor provides the test blades. Cooling air to the test blade sector is supplied from a laboratory air system independent of the system which supplies cooling air to the remaining 71 slave blades. The engine draws combustion air from the test cell. Because the research engine consists of only the high pressure spool of a two spool engine, the engine inlet air is preheated in order to simulate the inlet environment that the high pressure spool was designed to accept. The exit temperature from the preheater can be controlled automatically from about 353 K to about 478 K (175° to 400° F).

The control used to cycle the research engine between idle and cruise conditions is accomplished primarily by controlling the combustor fuel (ASTM A1) supply, as shown in figure 1. When valve A is closed, the entire fuel supply is fed to the combustors. Valve B is used to control the fuel flow to the combustors for the high temperature portion of the cycle. When valve A is opened, a portion of the fuel is recirculated, thus decreasing the fuel supply to the combustors. Valve C is used to adjust the fuel flow for the low temperature portion of the cycle. A separate control is provided to regulate the natural gas fuel supply to the preheater, as shown in figure 2. The control is accomplished by providing two sets of valves connected in parallel. The preheater fuel supply flowed through either valve A or valve B during cruise or idle conditions respectively. Controlling the fuel supply of both the combustor and the preheater permits the widest possible gas stream temperature excursions in the transient tests. The fuel control systems are cycled automatically by two separate timers. The preheater fuel control timer can be set to either lead or lag the combustor fuel control timer by a

pre-determined amount of time. The timers are activated by an electronic signal.

Blade Description

The blade cooling configuration tested during this investigation was identical to the simple cast blade configuration of reference 7. The blade span was 10.2 centimeters (4.0 in.) and the midspan chord length was 4.06 centimeters (1.60 in.). A cutaway view of this cast blade is shown in figure 3. Cooling air entered the blade through two cooling passages in the base and flowed radially outward and exited through the blade tip. Stiffeners A and B divided the cooling cavity into three regions. Each of the stiffeners contained 13 slots which permitted cooling air to pass between the leading edge and midchord regions and between the trailing edge and the midchord regions of the blade. Each slot was 0.63 centimeter (0.25 in.) long. The slots were 0.10 and 0.076 centimeter (0.04 and 0.03 in.) wide in stiffeners A and B respectively. Stiffeners A and B had about 80 percent flow area. The blade also had 19 spanwise fins of varying lengths in its midchord region. Nine of these fins were on the blade suction side, and 10 on the blade pressure side of the central cooling passage.

The blades were cast in a single piece and were supplied by the contractor from whom the test engine was purchased.

INSTRUMENTATION

Instrumentation used in the engine tests can be separated into two categories: operational instrumentation and research instrumentation. The instrumentation giving operational data such as engine rotative speed, oil pressure, oil temperature, fuel flow, coolant water flow, cooling air flow, etc. was used to set data points and to monitor the general condition of the research engine. Most of this instrumentation was connected to a central data recording station as well as to visual readouts in the control

room. The operational instrumentation is described in more detail in reference 6. The research instrumentation was designed to provide data for detailed analysis of the temperature distributions around the test blades. A brief description of the research instrumentation is given below:

Research Instrumentation

The purpose of the research instrumentation was to provide detailed information on the gas stream conditions, the cooling air flow conditions, and the blade wall temperature distributions.

Eight thermocouple probes were located at eight circumferential positions at the combustor exit plane to obtain the turbine stator inlet temperatures. Each of these traversing probes measured temperature at nine radial locations. The total turbine inlet temperature, considered as a representative average turbine stator inlet temperature, was obtained by averaging the measurements at three of the nine radial positions for all eight thermocouple probes.

The combustion air static pressure at the inlet to the combustor was also measured. According to the engine manufacturer, this pressure is nearly equal to the turbine inlet total pressure for the research engine, and can be used as such. This assumption implies that the pressure loss through the combustor is approximately equal to the dynamic head at the combustor inlet. Test data from the research engine indicated that this assumption appears to be reasonable. Therefore, in this report, the combustor inlet static pressure is used as the turbine inlet total pressure. The temperature and pressure of the cooling air was measured in the test blade cooling air annular chamber upstream of the rotating turbine disk. The temperature of the coolant was also measured at the blade base just before it entered the cooling air passages. The blade cooling air flow rate was measured by a calibrated venturi located in the coolant supply system external to the engine. Because of leakages in the cooling air system downstream of the measuring venturi, the total mass flow rate delivered to the test blades was calculated based on momentum pressure loss, rotational

pressure rise, and a calibrated friction pressure loss. Details of the calculation procedure are given in reference 8.

Four of the five test blades were instrumented with Chromel-Alumel thermocouples imbedded in the airfoil walls in order to obtain the blade chordwise temperature distribution. A total of 11 thermocouples were used. Figure 4 is a composite layout of the thermocouple locations. The thermocouple locations are given in table I. All thermocouples except thermocouple 8 were located 2.54 centimeters (1.0 in.) from the platform. Thermocouple 8 was located at 5.21 centimeters (2.05 in.) from the blade platform.

The construction of the thermocouple assemblies consisted of Chromel-Alumel wire with magnesium oxide insulation in an Inconel 600 sheath. These assemblies were drawn to 0.051 centimeter (0.020 in.) outside diameter, with a closed and grounded thermocouple junction at one end. A detailed description of the construction and installation procedure of the thermocouples is given in reference 9.

EXPERIMENTAL PROCEDURE

The experimental procedure for the transient tests involved setting the engine conditions manually at cruise and idle conditions by adjusting the fuel flow valves. The valves were then locked into position and the engine was cycled automatically between the cruise and idle limits by opening or closing the "on-off" valves in the engine fuel system. An automatic timer control mechanism was activated to cycle the engine between idle and cruise conditions over a 6-minute cycle. From an idle condition, the control closes valve A in the engine fuel bypass line (fig. 1), causing the engine to accelerate from idle to cruise. The control also activates a separate preheater timer-control, which closes valve A and opens valve B, causing the preheater exit temperature to rise to 450 K (350° F). The preheat automatic timers control can be set to lead or lag the combustor fuel control by a predetermined amount of time. After three minutes, the automatic control opens valve A and closes valve B in the preheater control,

and opens valve A in the combustor fuel control, causing the engine to decelerate from cruise to idle condition. The idle condition was held for 3 minutes. This six minute engine cycle was automatically repeated fifteen times. Transient data were recorded during the first, seventh, and fifteenth cycles.

DATA ACQUISITION

During the engine cycles, the transient test data were taken by high speed recorders capable of making up to 30 000 samples per second. The data selection, gain settings, recording rates, and the number of temperatures, pressures, and flow rates were all programmed on the automatic high speed recording system.

The transient data of this investigation were recorded at the rate of 5000 samples per second. Each temperature, pressure, and engine wheel speed was sampled at every 0.01 second of the transient test. To eliminate random background electronic noise, five successive values (over a time of 0.05 sec) of a given temperature or pressure were averaged to give one value of temperature or pressure. The smoothed values of temperature, pressure, and wheel speed are the ones reported herein.

RESULTS AND DISCUSSION

Experimental transient turbine blade temperatures were obtained from tests conducted in a research turbojet engine with the gas stream temperature cycling between 1567 and 1067 K (2360° to 1460° F). Transient values of engine gas stream temperature, pressure, and wheel speed were obtained during the acceleration and deceleration portions of a cycle, representing the transient from cruise to idle and back to cruise conditions. The turbine inlet pressure was about 26.2 N/cm² (38 psia) at cruise, and 22.4 N/cm² (32.5 psia) at idle conditions. The coolant inlet temperature was maintained at about 811 K (1000° F). The coolant flow was adjusted such that the

maximum blade temperature of about 1200 K (1700⁰ F) was attained at cruise conditions.

Engine Operating Conditions

Engine preheater exit temperature. - Because the research engine incorporated a combustion air preheater, as discussed previously in the APPARATUS section, the engine operation was influenced to some extent by the preheater operation. In order to understand some of the time-temperature relationships of the engine operating conditions, it is convenient to first understand the time-temperature behavior of the preheater during engine acceleration and deceleration. For the acceleration tests, the preheater was scheduled to increase the gas stream temperature about 1.25 seconds before engine fuel flow was increased. For the deceleration tests, the preheater was scheduled to reduce the gas stream temperature about 0.5 second after the engine fuel flow was decreased.

Figure 5 shows the typical relationship of the preheater exit temperature (essentially the compressor inlet temperature) with time. In this report, the time at which the automatic timing device initiated the electrical impulse to increase or decrease the fuel flow to the engine is referred to as "time zero." In figure 5, it can be seen that during a typical acceleration cycle, the preheater exit temperature starts to increase about minus 1.25 seconds before time zero, and increases nearly linearly from about 346 K (162⁰ F) to about 378 K (220⁰ F) in approximately 3 seconds of total elapsed time. After 3 seconds, the exit temperature increases steadily but at a slower rate until at 20 seconds after time zero, the temperature has increased to about 408 K (275⁰ F). At equilibrium conditions, the preheater exit temperature is about 430 K (314⁰ F). During the deceleration cycle, the preheater temperature starts to decrease at about 0.5 second after time zero, and continues to decrease until an equilibrium temperature of about 345 K (160⁰ F) is reached.

Engine fuel flow. - The variation in engine fuel flow during a typical acceleration and deceleration cycle is shown in figure 6. The fuel flow is presented in terms of the fuel meter frequency in cycles per second, which is proportional to the volumetric fuel flow in cubic meters per second (gal/sec). During acceleration, the fuel flow starts to increase immediately when the electric impulse is given to close valve A (fig. 1) of the engine fuel control system. In 0.5 second, the fuel flow has increased from the idle fuel flow setting to about 82 percent of its total change. After 2 seconds of elapsed time, the fuel flow rate has essentially reached its steady state value at cruise condition. In the deceleration, the fuel flow decreases rapidly starting about 0.25 second after the electric signal has been given to open valve A in the engine fuel control system. The time lag between time zero and the initiation of deceleration is attributed to the inherent characteristics of the control system during deceleration. At 1 second after time zero, the fuel flow has reached nominally 95 percent of its total change. At 2 seconds after time zero, the fuel flow has essentially reached the steady state value for idle conditions.

Turbine inlet temperature. - The variation of turbine inlet temperature with time during acceleration and deceleration is shown in figure 7. During acceleration, the temperature starts to increase about 1.25 seconds before time zero, due to the preheater start. At 2 seconds after time zero, the turbine inlet temperature increased from an idle steady state value of 1067 K (1460° F) to about 1505 K (2250° F) or 95 percent of its steady state cruise level. After time zero plus 2 seconds, the turbine inlet temperature increases slowly until it reaches steady state cruise condition of 1567 K (2360° F).

During deceleration, the turbine inlet temperature shows a rapid decrease in temperature approximately 0.25 second after time zero. This time lag in temperature also corresponds to the time lag in engine fuel flow during deceleration as shown in figure 6. After about 12 seconds, the turbine inlet temperature has reached 87 percent of the total change in temperature that occurs in the deceleration phase of the engine temperature cycle.

Engine rotative speed. - Figure 8 shows the transient response in engine rotative speed. During acceleration, the engine speed is affected only slightly by the increase in the preheater exit temperature during the 1.25 seconds before time zero. At time zero, as the engine fuel flow is increased, the engine speed accelerates rapidly for about 10 seconds and then levels off to a slow increase until the steady state cruise rotative speed of 8200 rpm is reached. During deceleration, the engine speed decayed rapidly, starting approximately 0.25 second after time zero. The time lag from time zero for the engine speed decay again corresponds to the time lag for the engine fuel flow during deceleration, as shown in figure 6. Figure 8 shows that for both acceleration and deceleration, the engine speed reached a nominal 90 percent level of its total change within about 14 seconds of the initial engine fuel flow change.

Turbine inlet total pressure. - Recall from the discussion in the INSTRUMENTATION section that the turbine inlet total pressure used in this report is actually the static pressure measured at the combustor inlet. Figure 9 shows the variation of the combustor inlet static pressure with time during acceleration and deceleration. During the initial portion of the acceleration, the pressure decreased markedly from the engine idle level of about 22.4 N/cm^2 (32.5 psia) to a level of about 20.3 N/cm^2 (29.5 psia). This decrease in pressure 1.25 seconds prior to time zero corresponds to the time at which the preheater temperature was increased (see fig. 5). The reason for the pressure decrease was attributed to the conversion of some static pressure into dynamic head during the transient when the preheater exit temperature was increasing. The pressure increased rapidly from time zero, when the engine fuel flow was increased, until at time zero plus 10 seconds, the steady state pressure of 26.2 N/cm^2 (38 psia) at cruise condition was reached. During deceleration, the pressure decay lagged time zero by about 0.25 second. This was due to the fact that the engine fuel flow lagged time zero by about 0.25 seconds during deceleration, as was seen in figure 6. The pressure then recovered somewhat between time zero plus 0.5 second and time zero plus 1.5 seconds. The pressure then decreased steadily until about time zero plus 20 seconds, and then remained steady at the engine idle pressure level of about 22.4 N/cm^2 (32.5 psia). The temporary pressure increase at 0.5 second after time zero was

attributed to the conversion of some dynamic head into static pressure when the preheater turn down occurred.

Blade Temperatures

The test blade temperature distribution as a function of time is shown in figure 10. Figure 10(a) shows the transient temperature response during the acceleration phase of the cycle. Thermocouple number 7 was inoperative during the transient tests, so only steady state values are shown for this location.

The blade temperature at each thermocouple location increased with time, as expected when the engine accelerated from idle to cruise condition. The maximum chordwise temperature difference was 76 K (136° F) during engine idle and 217 K (391° F) during cruise. Hot spot blade temperatures occurred at the leading and trailing edges during engine idle. They also occurred at these same locations throughout the acceleration period. There was no reversal of temperature profile from convex to concave (or vice versa) at any time during acceleration, in contrast to the thermal response of the vanes reported in reference 5.

The lack of a reversal in the temperature gradients in the blade is attributed to the difference in heat sink capacity of the blade stiffener near the leading edge "gill" region, as compared to the vanes. As was noted under "BLADE DESCRIPTION," the blade stiffener contained slots that amounted to 80 percent open flow area. This is in contrast to the vane stiffener, which was solid and more massive. During acceleration and deceleration, the higher heat sink capacity of the vane stiffener caused the metal temperature in the stiffener region to lag the surrounding temperatures.

The blade stiffener, because of its lower heat sink capacity, did not cause a significant time lag in the metal temperature during the transient conditions.

There was a small increase in blade temperature from minus 1.0 seconds to time zero in response to the increasing turbine inlet temperature due to preheater ignition. The blade temperatures increased rapidly after

time zero when the combustor fuel control valve was actuated. The leading edge temperature reached 90 percent of its total response (i. e., change in temperature between idle and cruise values) about 11 seconds from time zero. For comparison, the gas stream temperature reached 90 percent of its total response in 3 seconds during engine acceleration.

Figure 10(b) shows the transient temperature response during the deceleration phase of the cycle. Again as expected, the blade temperature at each thermocouple location decreased with time as the engine decelerated from cruise to idle. The maximum chordwise temperature difference was 219 K (394° F) during cruise, and 77 K (139° F) during engine idle. Hot spot blade temperatures, which occurred at the leading and trailing edges at cruise condition also occurred at the same locations throughout the deceleration period. No reversal of temperature profile from convex to concave (or vice versa) was noted at any time during the deceleration. Unlike the acceleration portion of the cycle there was no change in the blade temperatures from minus 1.0 second to time zero. This was due to the fact that the engine environment did not change during this period. In the deceleration, the leading edge temperature reached 90 percent of its total response in 19 seconds from time zero. For comparison, the gas stream temperature reached 90 percent of its total response in 5 seconds during engine deceleration.

Cycle Data Repeatability

Transient data were recorded during the first, seventh, and fifteenth cycles of the transient test. Figure 11 compares the transient temperature at the blade leading edge (thermocouple 1) for cycles 1 and 15. The figure shows that the blade temperature was repeatable to within 3.9 K (7° F). Comparison at other thermocouple locations produced similar results.

Figure 12 compares the transient turbine inlet total pressure for cycles 1 and 15. The figure shows that the turbine inlet total pressure was repeatable to within 0.32 N/cm² (0.47 psia) throughout the elapsed time span. Comparison of cycle 7 with either cycle 1 or cycle 15 gave similar results.

SUMMARY OF RESULTS

Experimental transient blade temperatures were obtained from tests conducted in a research engine, as the main gas stream temperatures in the engine were cycled between 1090 and 1590 K (1500° and 2400° F). Local blade temperatures were obtained during the acceleration and deceleration portions of the cycle, representing the transient from idle to cruise, and back to idle conditions. Several results obtained from these tests are listed as follows:

1. The engine temperatures, pressures, and wheel speed during the transient tests correlated closely with the engine fuel flow and preheater exit temperatures. The blade temperature response also could be related to the transient engine environment data.

2. The blade leading edge temperature reached 90 percent of its total response (i. e. , the difference between idle and cruise values) in 11 seconds during acceleration, and 19 seconds during deceleration. The gas stream temperature reached 90 percent of its total response in 3 and 5 seconds, during engine acceleration and deceleration, respectively.

3. The blade temperature distribution did not exhibit a reversal of temperature profile, as was the case of the vane in a similar transient test. The lack of a temperature profile reversal in the blade was attributed to the smaller heat sink capacity of the blade stiffener.

4. The blade leading edge temperature transients were repeatable between the first and last cycles (cycles 1 and 15) to within 3.9 K (7° F). The turbine inlet total pressure transients were repeatable between the first and last cycles to within 0.32 N/cm² (0.47 psia).

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TABLE I - TEST BLADE THERMOCOUPLE LOCATIONS

Thermocouple number	Ratio of distance along surface to total surface length, ^a x/L_s or x/L_p	Radial distance from blade platform	
		cm	inches
1	.015	2.54	1.00
2	.301	2.54	1.00
3	.527	2.54	1.00
4	.800	2.54	1.00
5	1.000	2.54	1.00
6	.558	2.54	1.00
7	.330	2.54	1.00
8	.082	5.21	2.05

^a ^{total} Suction side surface length (L_s) = 5.08 cm (2.037 in.); pressure side total surface length (L_p) = 1.33 cm (1.704 in.)

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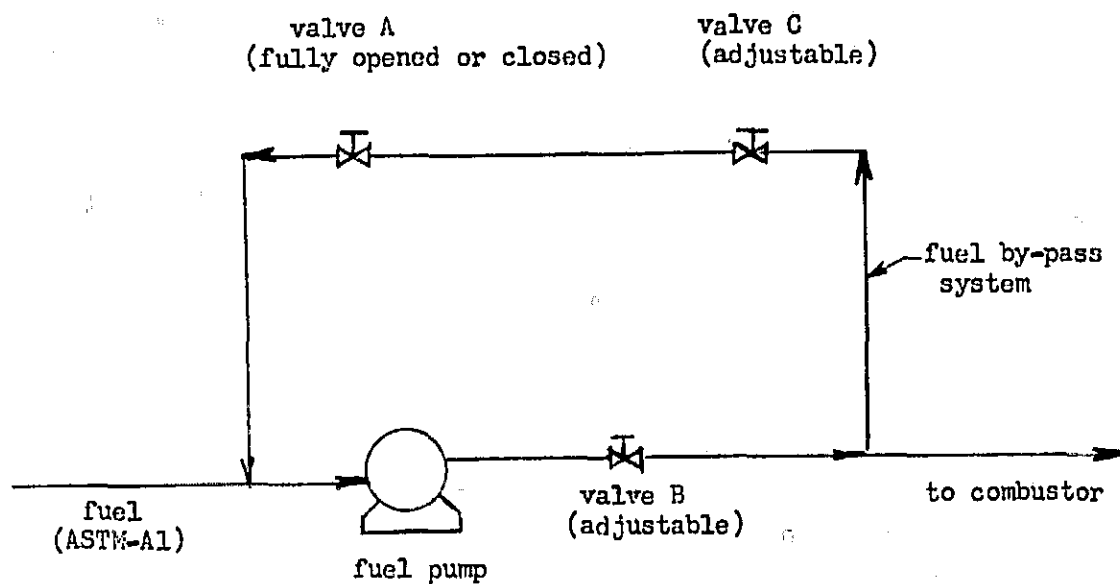


Figure 1. Schematic diagram of engine fuel control system

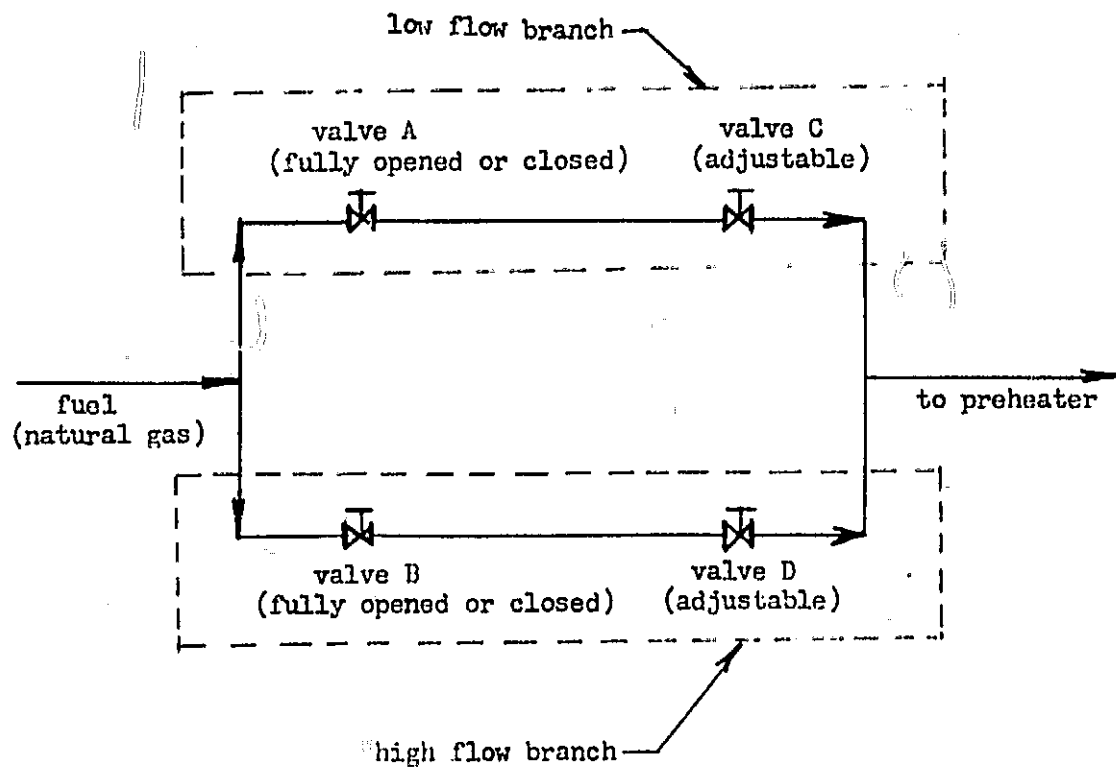


Figure 2. Schematic diagram of preheater fuel control system for combustion air preheater.

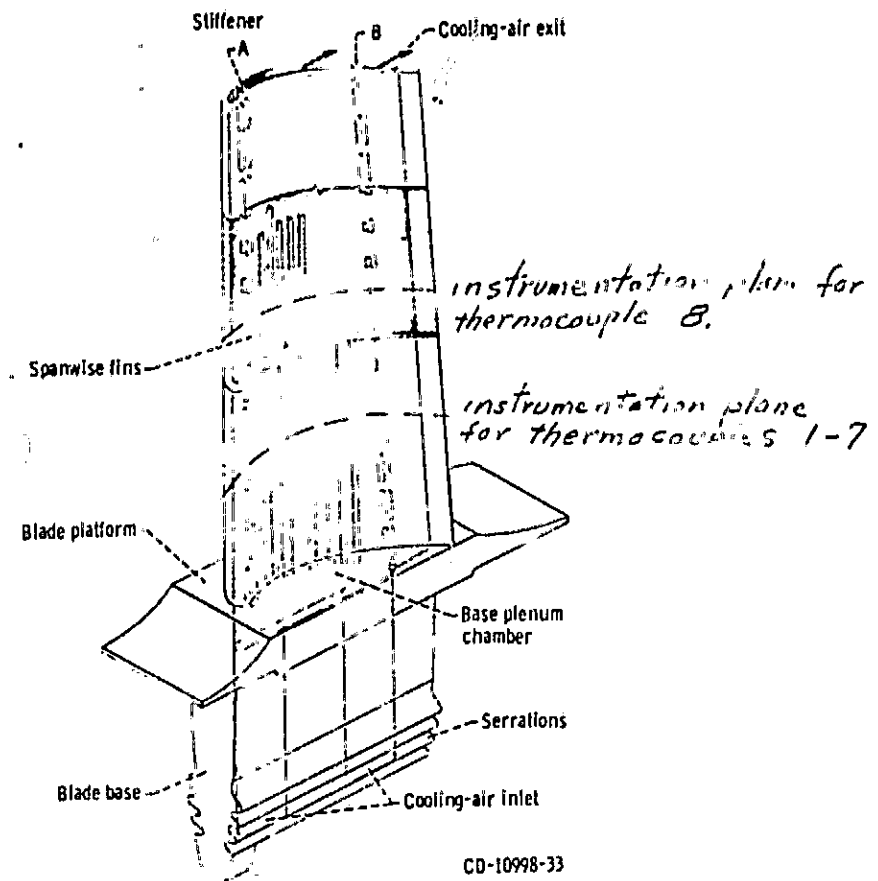


Figure 3 - Cut away view of test blade

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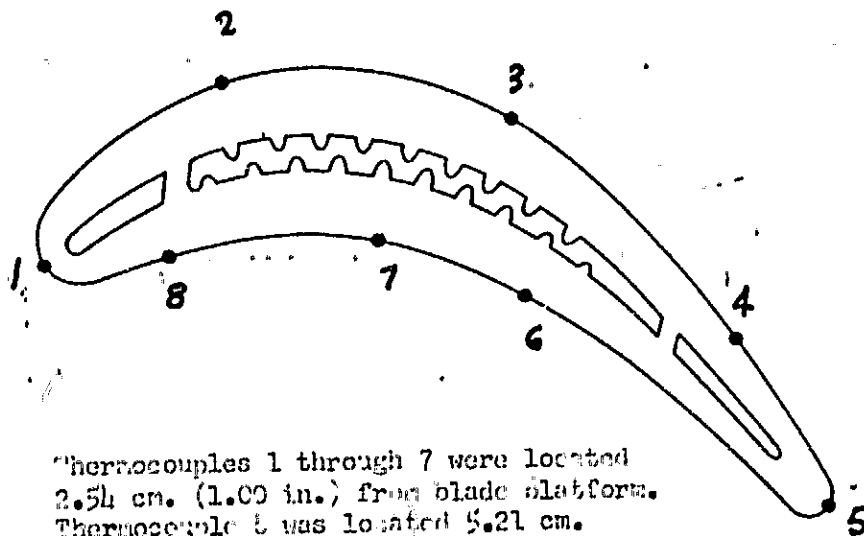


Figure 4 - Blade composite thermocouple locations.

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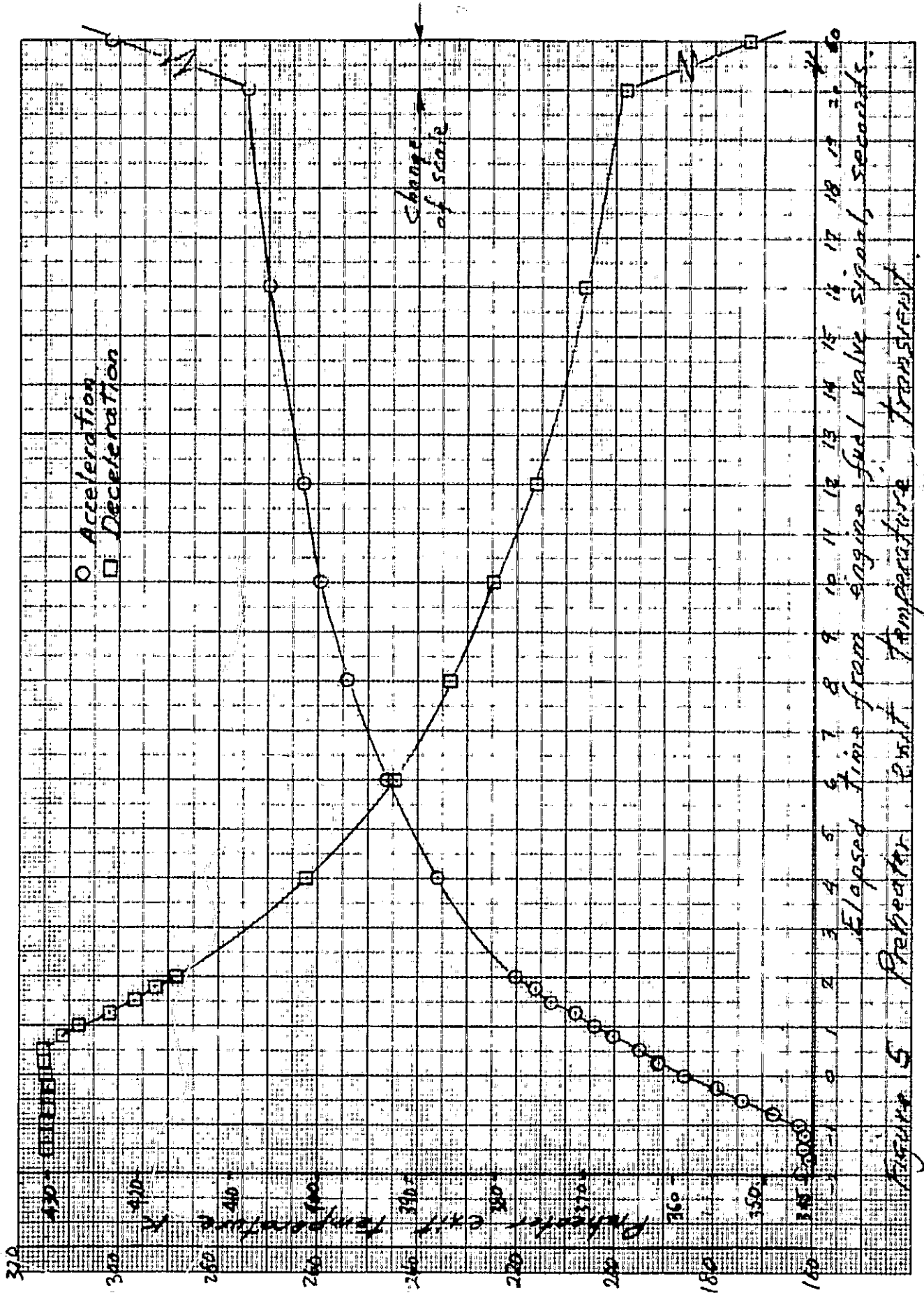
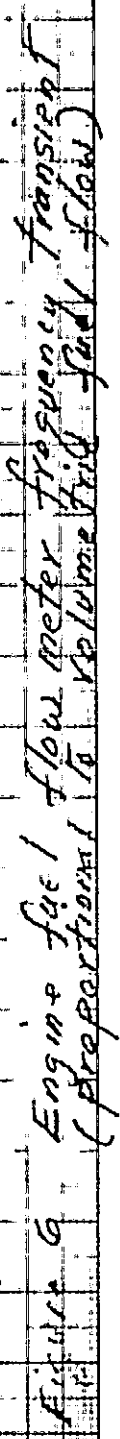
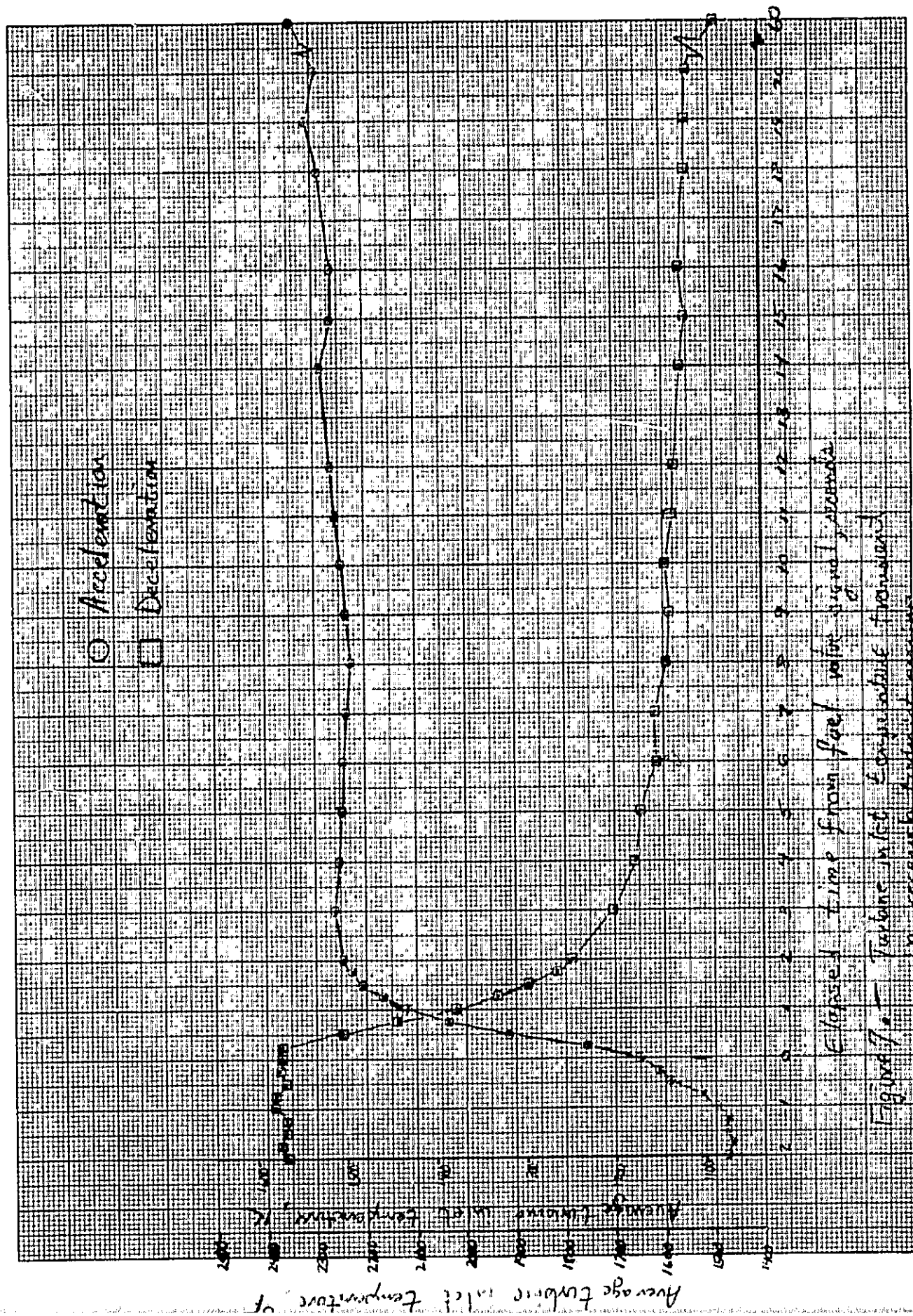


Figure 5 Preheater exit temperature transient





Elapsed time from fuel valve signal, seconds
 Figure 7. Turbine inlet temperature transient in research turbojet engine.

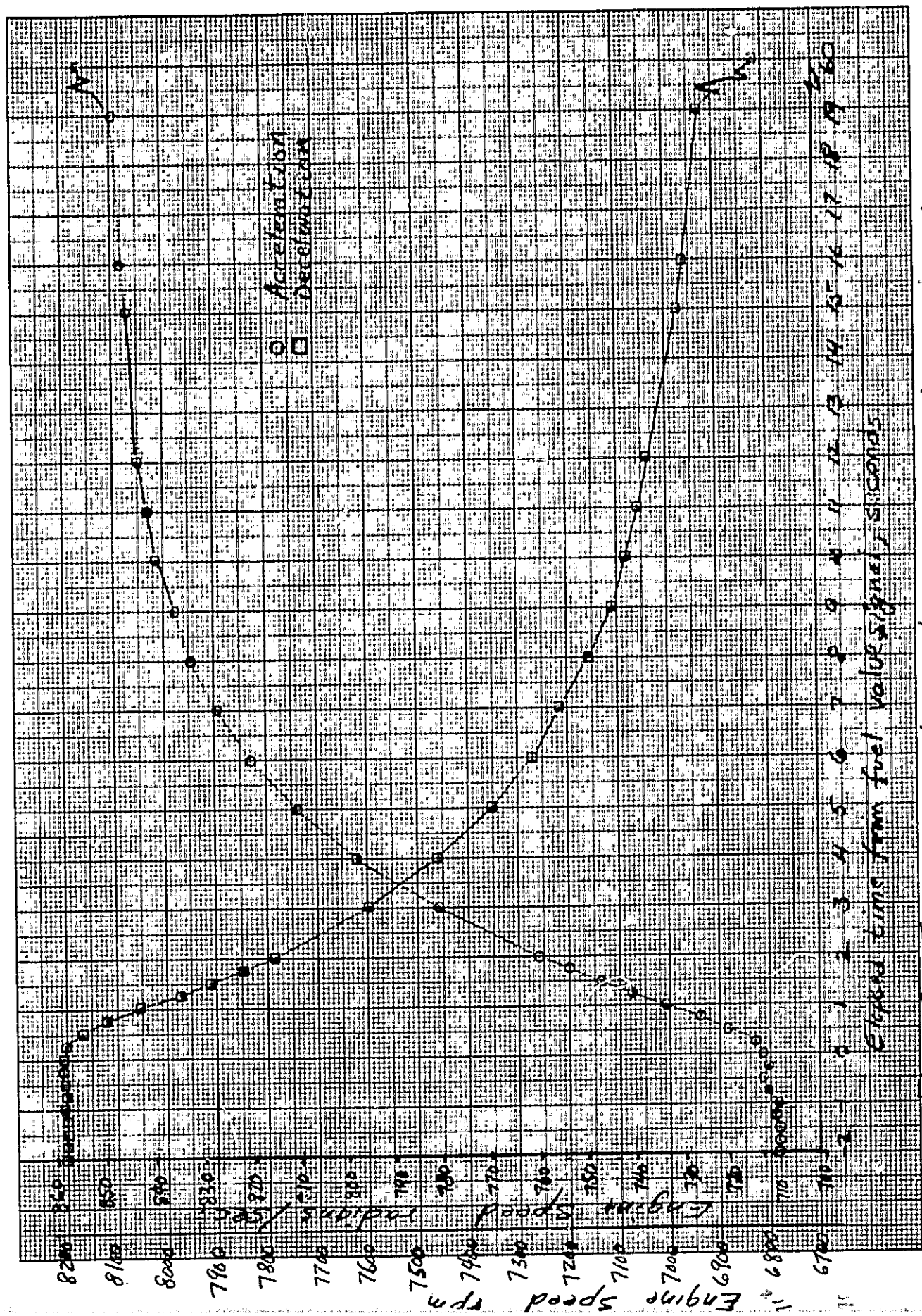


Figure 8.—Engine speed transient in research turbopump engine.

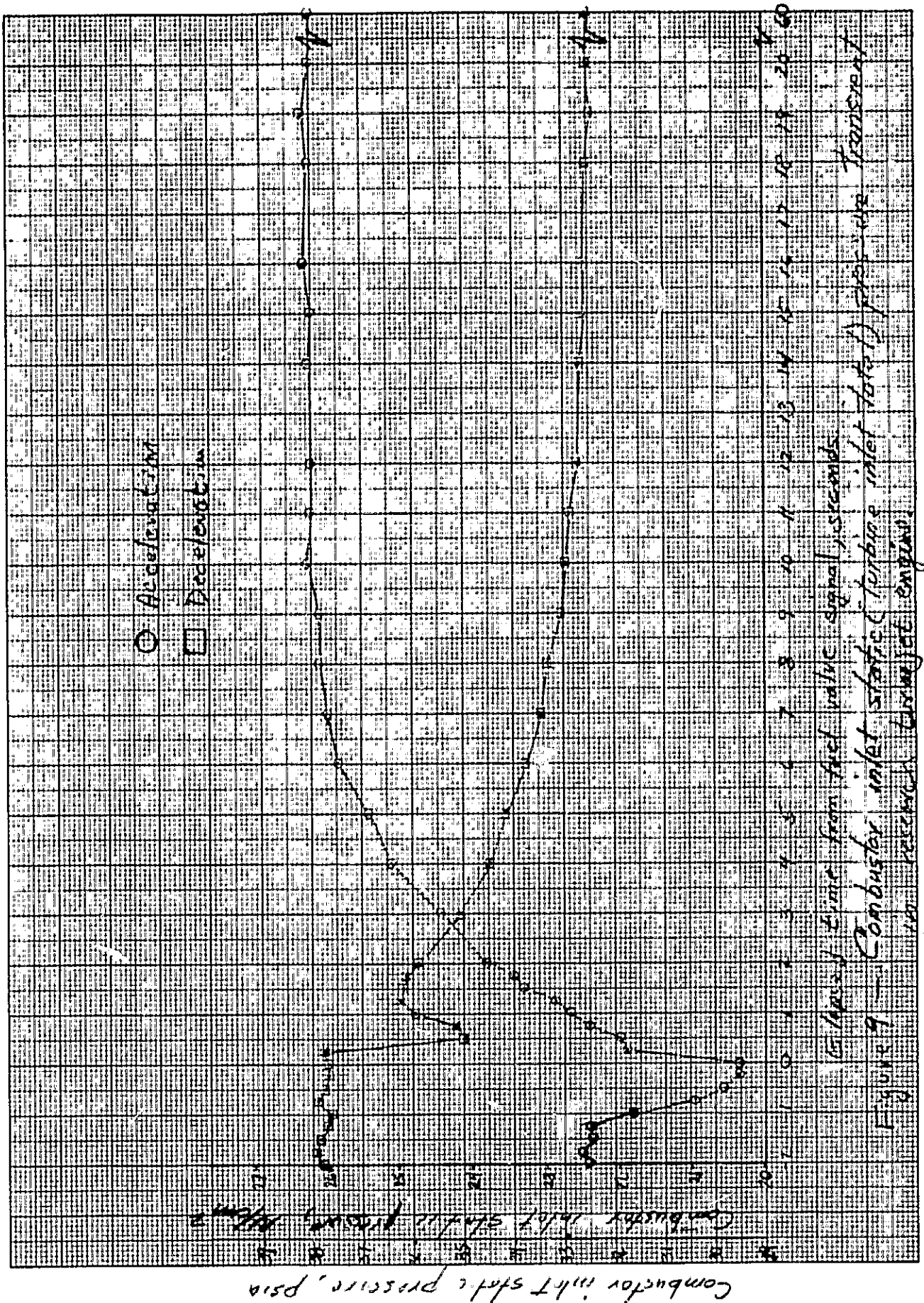


Figure 9 — Combustor inlet static pressure inlet total pressure transient
 (Elapsed time from fuel valve signal, seconds)
 100 percent thrust engine

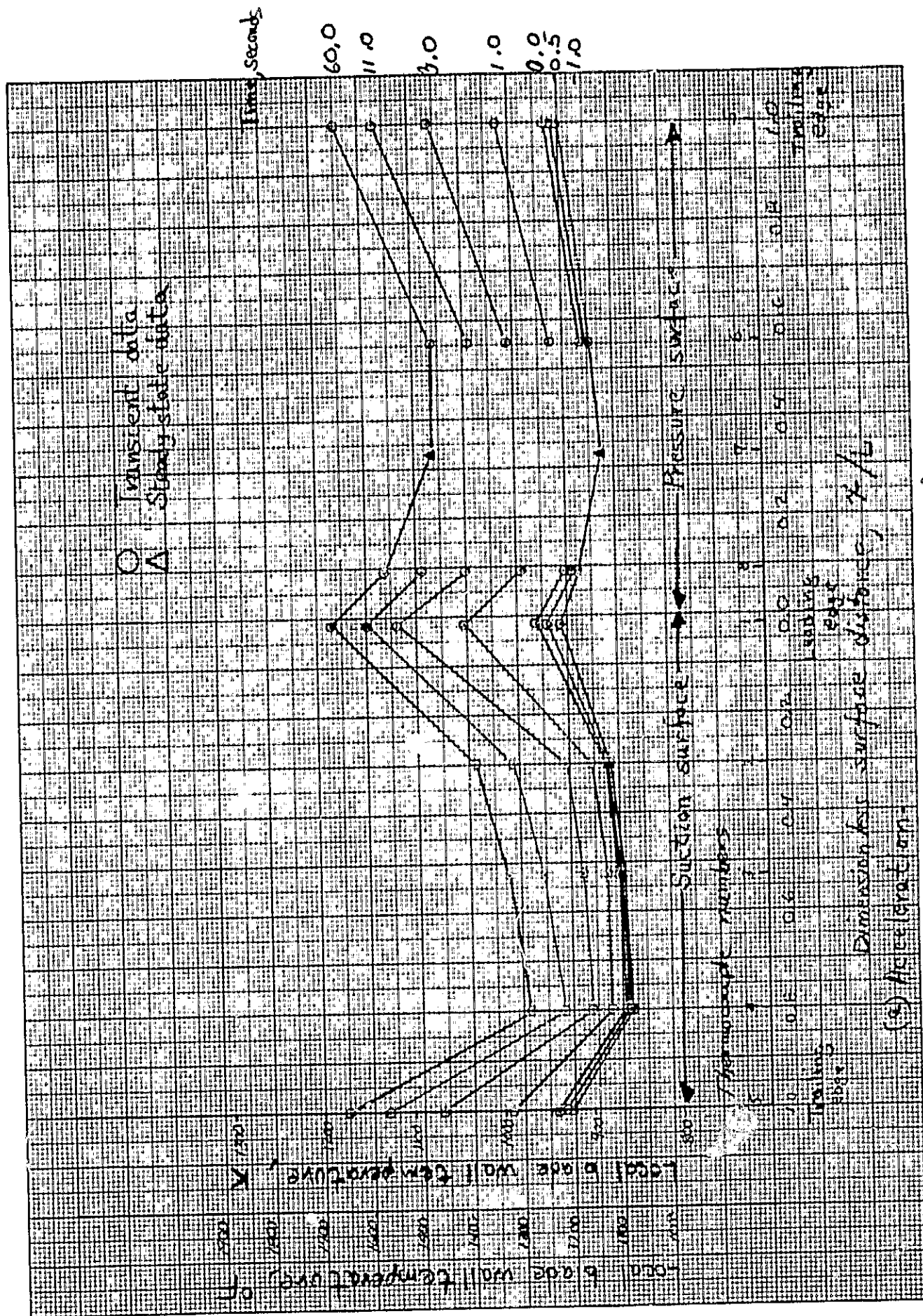


Figure 10- Transient temperature response of blade wall.

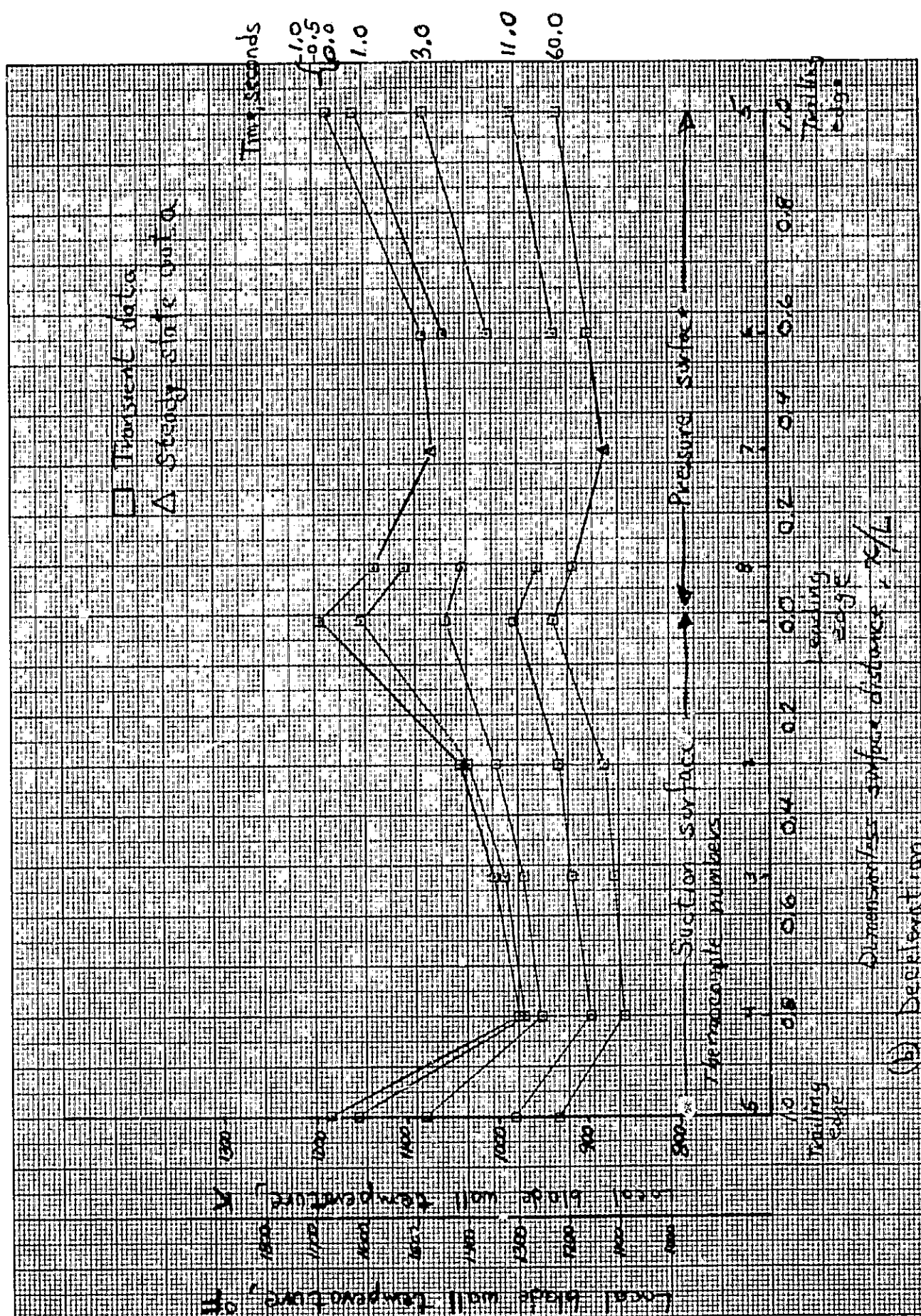


Figure 10- concluded.

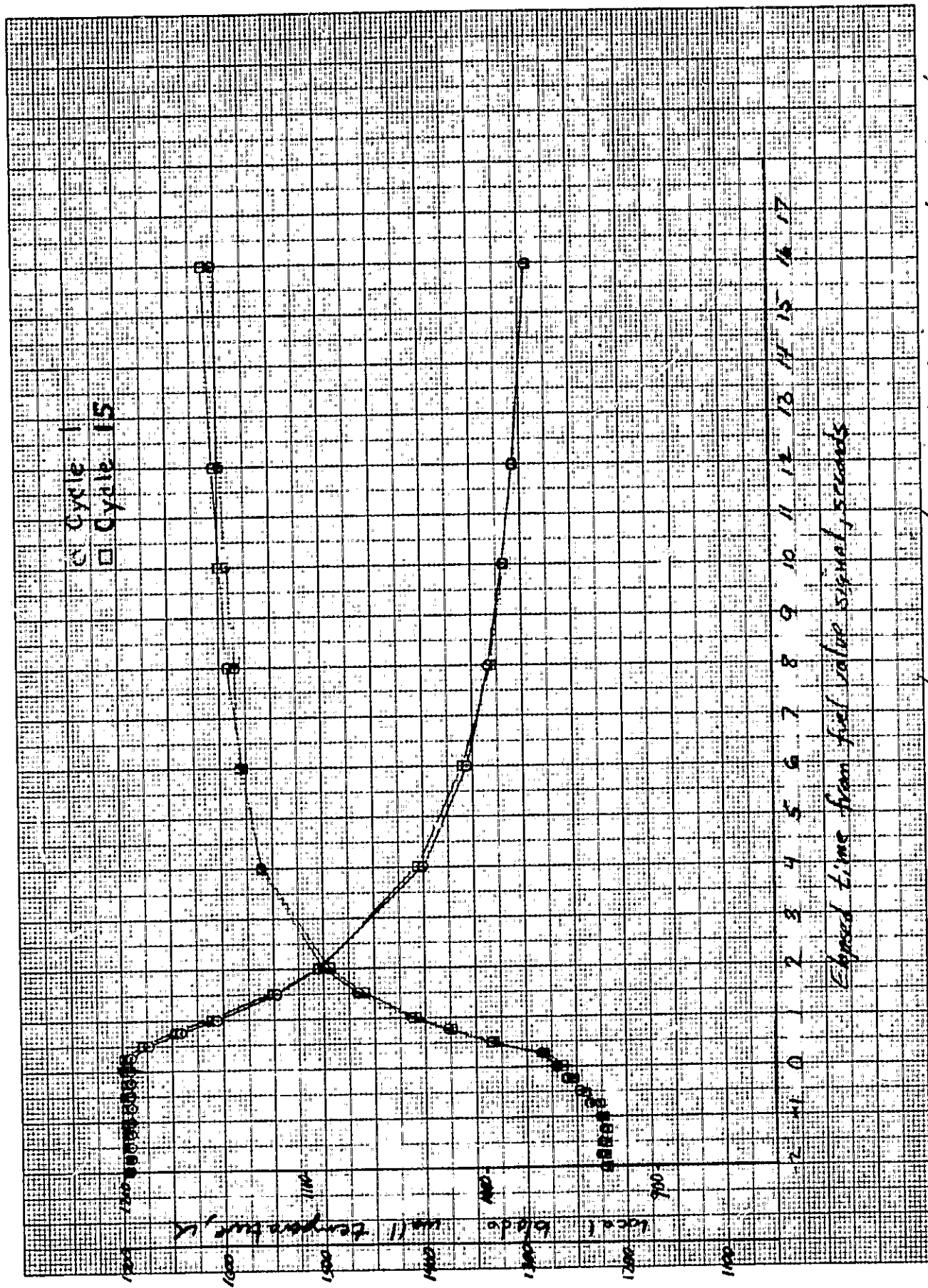


Figure 1.1 - Blade heating in response to transient aero cycles 1 and 15

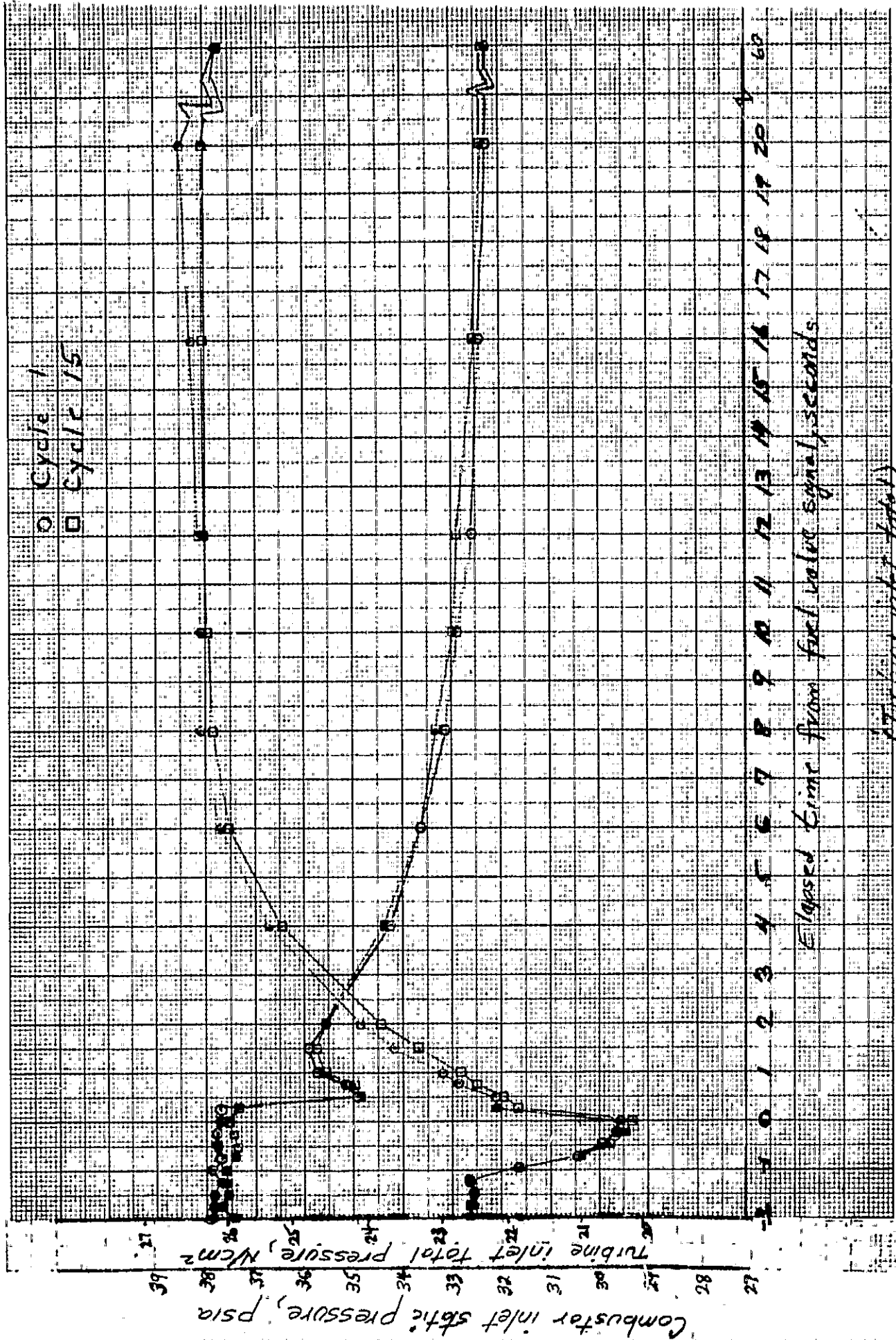


Figure 12 Combustor inlet static pressure transient during cycles 1 and 15.